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ANALYSIS OF EXPLOSION SEVERITY OF TEA POWDER AT DIFFERENT PARTICLE SIZE AND CONCENTRATION IN A CONFINED SPACE

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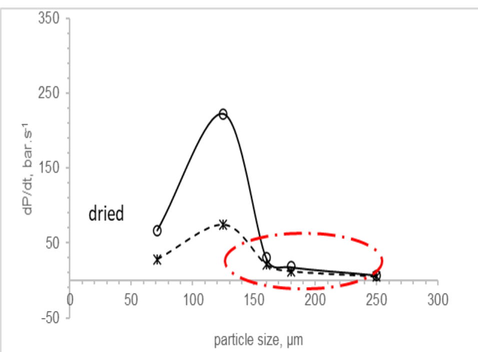
Graphical abstract



Abstract

Tea contains compounds rich in carbon-hydrogen bonds. When tea dust is suspended in air, across a variety of particle sizes and concentrations, in the presence of spark, it can combust, therefore presenting an explosion hazard. The explosion pressure properties of tea dust of four different dust concentrations (1000 g/m³, 1500 g/m³, 2000 g/m³ and 2500 g/m³) were conducted in a 20-L spherical explosion test vessel under five distinct particle sizes (71 µm, 125 µm, 160 µm, 180 µm and 250 µm). According to the findings, the explosion pressure characteristic is strongly related to dust concentration and particle size. Moisture content also has an effect on explosion propagation. The dried tea dust reached the maximum explosion pressure faster than undried tea dust. Among of the concentration and particle size range tested, the highest explosion pressure, 14.6 bar, was recorded at 2000 g/m³ with particle size 125 µm. The explosion index was 222 bar/s. It was shown that at higher dust concentration (≥2000 g/m³) and smaller particle sizes (≤125 µm) the explosion became more severe, whereby the flame accelerated at a higher rate and raised the explosion pressure drastically. The pressure characteristic changed as the conditions in which they occurred changed. These analyses and predictions are essential for achieving safe and optimal performance of tea manufacturing technology as well as the development of new applications.

Keywords: Dust, flame, rate of pressure rise, explosion, propagation

Abstrak

Teh mengandungi sebatian yang kaya dengan ikatan karbon-hidrogen. Apabila habuk teh berada di udara, merentasi pelbagai saiz dan kepekatan zarah, dengan kehadiran percikan api, ia boleh terbakar hingga menyebabkan bencana letupan. Sifat tekanan letupan habuk teh terhadap empat kepekatan habuk yang berbeza (1000 g/m³, 1500 g/m³, 2000 g/m³ dan 2500 g/m³) dikaji dalam alat uji letupan sfera 20-L pada lima saiz zarah yang berbeza (71 µm, 125 µm, 160 µm, 180 µm dan 250 µm). Menurut hasil kajian, ciri tekanan letupan sangat berkaitan dengan kepekatan habuk dan saiz zarah. Kandungan kelembapan juga mempunyai kesan terhadap penyebaran letupan. Habuk teh kering mencapai tekanan letupan maksimum lebih tinggi berbanding habuk teh yang lembap. Di antara kepekatan dan julat saiz zarah yang diuji, tekanan letupan tertinggi, iaitu 14.6 bar, dicatatkan pada 2000 g/m³ dengan saiz zarah 125 µm. Indeks letupan adalah 222 bar/s. Ditunjukkan bahawa pada kepekatan habuk yang lebih tinggi (≥2000 g/m^3) dan saiz zarah yang lebih kecil (≤125 μm) letupan menjadi lebih teruk, di mana api merebak pada kadar yang lebih tinggi dan peningkatan tekanan letupan secara drastik. Ciri tekanan berubah sejajar dengan perubahan keadaan. Analisis dan ramalan ini penting untuk mencapai prestasi teknologi pembuatan teh yang selamat dan optimum serta pengembangan aplikasi baru.

Kata kunci: Habuk, api, kadar peningkatan tekanan, letupan, penyebaran

1.0 INTRODUCTION

Dust explosions have resulted in massive losses and damages to people, property and the environments. Combustible dust is defined as fine particles that, when suspended in air, pose an explosion or blast risk under specific conditions. To trigger a dust explosion, the dust should be flammable, dispersed in air at an explosive concentration, and there must be enough oxygen to support the combustion and sufficient energy to initiate the combustion [1-3]. According to Eckhoff [4], any particle which can combust in air may cause an explosion with increasing severity and subdivision.

Numerous production methods generate very small dust particles that can become airborne and accumulate on surfaces and in narrow passages or holes across the plant [5]. In Malaysia, for instance, tea powder is commonly consumed. Tea originated from China's South East and is now grown in most other countries worldwide, with over 82 distinct species. According to Adnan *et al*. [6], tea contains vitamins, volatile acids, amino acids, polysaccharides, alkaloids (caffeine, theophylline, and theobromine), lipids, polyphenols (flavonoids and catechins), and inorganic elements. Tea dust processing can generate a lot of dust, which can pose to a dust explosion.

Dust explosions are common in industries and processes that handle a variety of organic and inorganic powders and dust [7]. The dust explosion sensitivity parameter, the chemical property of the dust and the dust explosion severity characteristics such as the maximum explosion pressure (P_{max}) and the rate of pressure rise (dP/dt) as well as the dust deflagration index (K_{St}) are implemented to avoid such an accident [8-10]. There have been many publications regarding dust explosion in the literature but so far there has been no data on the explosibility of tea powder from Asia. It is important to identify the factor influencing tea powder explosion.

As a result, basic information on the tea powder's physical and chemical properties, as well as its moisture content and volatility, will be provided in this study. The data on explosibility includes the maximum explosion overpressure (P_{max}), minimum concentration of explosibility (MEC) and dust deflagration index (K_{St}). MEC is crucial because handling of the dust can result in the formation of a potentially explosive dust cloud [11]. Depending on the severity of the dust, P_{max} and K_{St} have been extensively studied in order to develop effective dust explosion safety measures such as inerting, suppression, or explosion relief venting [12].

2.0 METHODOLOGY

2.1 Characterization of Tea Powder

A commercial black tea leaf powder purchased from the local stores was used as the sample in this study. The tea dusts were ground in a high-performance laboratory grinder before sieving into five different sizes: 71 μm, 125 μm, 160 μm, 180 μm and 250 μm. A Malvern Mastersizer was used to measure the distribution of particle size (PSD) as defined by the volume weighted mean (model Scirocco 2000). The thermogravimetric analysis (TGA) technique was used to determine the chemical and physical properties of tea powder. The TGA curves (TA instruments-Waters' TGA Q 500) were used to calculate the percentage of weight loss of tea powder of five various sizes. The component compositions were calculated using their certain temperature i.e. T = 105 °C for moisture content, T = 500 °C for volatiles, and T = 600 °C for fixed carbon, whereas ash was identified as the residual [6]. A morphology (texture), chemical composition, and microcrystalline orientation of the tea powder were determined using a scanning electron microscope (SEM-EDX) version FEI-Quanta 450.

2.2 Dust Explosion Testing

Figure 1 shows the explosibility characteristics of tea powder measured in a Siwek 20-L spherical vessel. The test vessel is a hollow stainless-steel sphere that can withstand pressures of up to 20 bar. A computer was connected to the test vessel, which used the KSEP control system to control the dispersion, firing series, and data analysis. Two 5 kJ chemical igniters were used in the explosion tests to represent the standard ignition source. The ignition leads were attached to the igniters. The ignition delay time, tv, for both undried and dried tea powder was set and fixed to 60 ms. Prior to the explosion test, the tea powder was dried for one hour at 105 °C in an oven at atmospheric pressure. The dust was then directly loaded into the 0.6-L dust pot then a blow of 20 bar (gauge) compressed air was dispersed via the attached rebound nozzle at the outlet valve which located at the vessel's bottom. The ignition source started the explosion test based on the ignition time. The dust concentration was varied at 1000 g/m³, 1500 g/m³, 2000 g/m³ and 2500 g/m³ to measure the changes in explosion pressure development. Two "Kistler" piezoelectric pressure sensors mounted on the vessel's wall measured the explosion pressure development. Three repeated tests were conducted on each parameter set, and the results showed high validity, with peak pressures ranging the in magnitude by or less 5%.

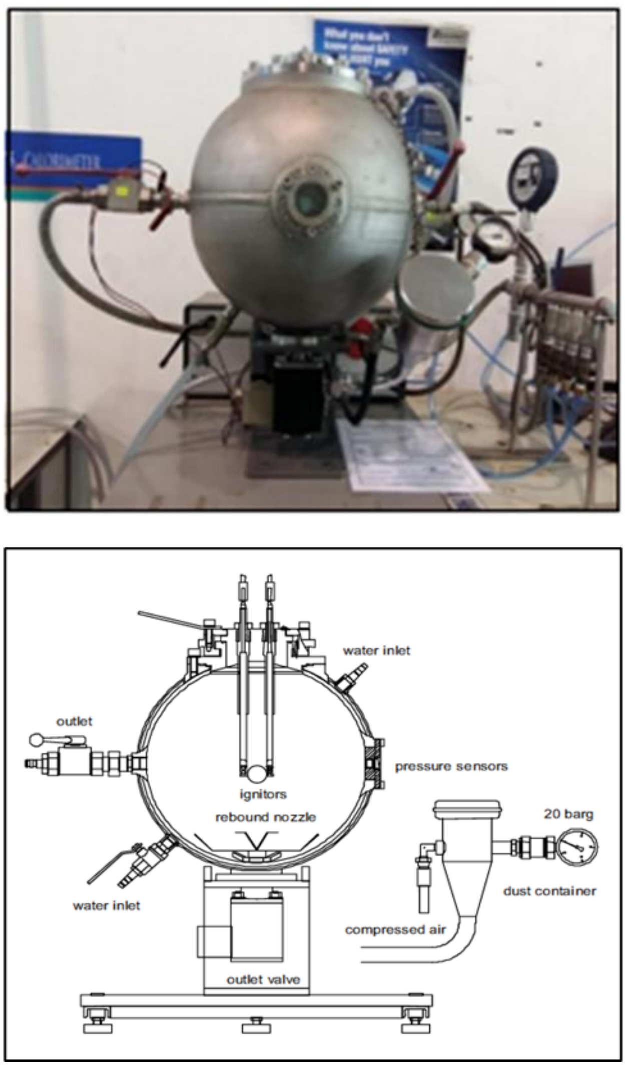


Figure 1 Schematic diagram of 20 L spherical explosion vessel [13]

3.0 RESULTS AND DISCUSSION

Table 1 summarises the chemical and physical properties of tea powder. The table shows that the particles are generally smaller than 500 µm, indicating that the tea powder has the potential to explode (Institute for Occupation Safety and Health). PSD of tea powder at size 71 µm and 250 µm are shown in Figure 2. The median diameter, D50 for particle size 71 µm is 65.29 µm while particle size 250 µm has it at 279.53 µm, means that more than 70% of the particles have a particle size smaller than the median particle size. A particle's specific surface area decreases as its size increases.

Table 1 Physical and chemical properties of tea powder

Size (µm)	Surface area (m²/g)	Moisture (%)	Volatility (%)	Ash (%)
71	0.39	6.52	64.78	4.97
125	0.26	8.87	60.51	5.09
160	0.10	9.08	56.30	5.41
180	0.03	10.52	53.37	22.73
250	0.02	13.54	51.23	23.18

According to Eades [14] and Segers *et al*. [15] finer dust is more likely to explode compared to coarser dust, which suggests that tea powder at a size of 71 µm would produce a stronger explosion while 250 µm would give a weaker explosive effect. The microstructure of tea powder (Figure 3) shows that tea consists of stacked and irregular shapes, which makes the tea powder easy to agglomerate and difficult to disperse [16-18]. This characteristic would affect the ignition process and reduce the explosion propagation. The moisture and ash content increase with the increment of particle size, as expected. Tea powder, on the other hand, has a lower volatiles content as particle size increases. From Table 1, it can be summarized that tea powder with particle size 250 µm is harder to ignite due to the high ash and moisture content as well as the low volatiles content compared to the finer particle size and vice versa.

3.1 Effect of Particle Size

P_{max} or the maximum explosion pressure in the explosion vessel after ignition determines the explosibility of tea powder at varied particle sizes. Figure 4 shows that for all sizes, the P_{max} for dried dust is twice that of undried dust. The moisture content in the undried dust acts as a heat sink, absorbing heat during the explosion process [19], leading to a lower P_{max} as shown in Figure 4. The highest P_{max} (14.61 bar and 6.65 bar) was recorded at particle size = 125 µm for both dried and undried particle condition and not at particle size 71 µm. This peculiar trend was suspected due to the dust particle's irregular shape. It is believed that the 71 µm tea powder has a severe irregular shape that makes it easy to agglomerate and difficult to disperse. This property hindered the explosive process and depressed the P_{max}.

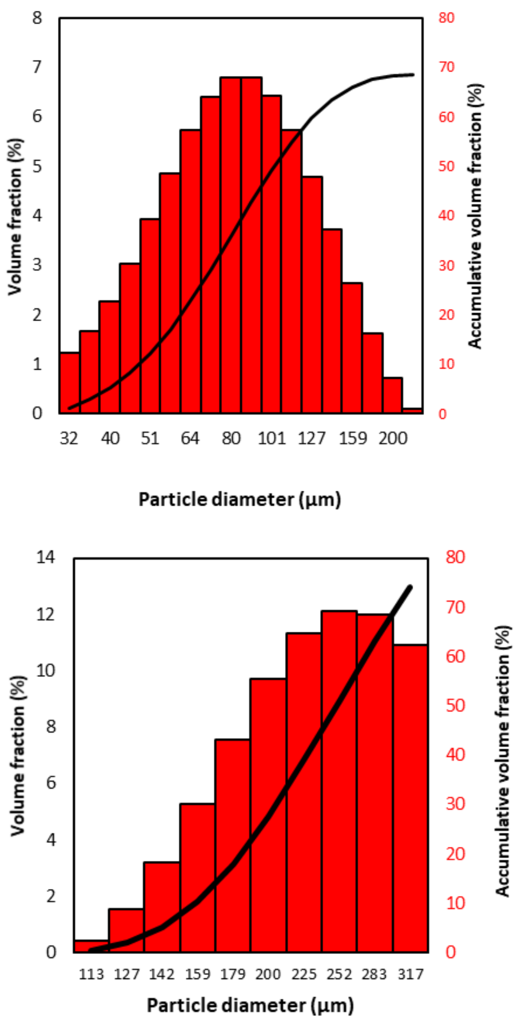


Figure 2 Graph of particle distribution for tea powder at 71 µm (top) and 250 µm (bottom)

As expected, beyond 125 µm, the P_{max} decreased significantly for both conditions. Aside from the effect of particle size, moisture content could also be a factor in this pattern. Moisture has been shown to minimize the level of static electricity required for ignition [20-21]. Referring to Table 1, as the particle size increases, so does the moisture content. The ignition of larger particles (160 µm, 180 µm, and 250 µm) is harder as a consequence, leading to decreased in P_{max} as particle size increases, as can be seen in Figure 4. Figure 5 also demonstrates that the dP/dt trend is consistent with P_{max} trend. This indicates that the worst tea dust explosion occurred at particle size 125 µm with a shock effect of 222 bar/s (dried particle) and 74 bar/s (undried particle) respectively.

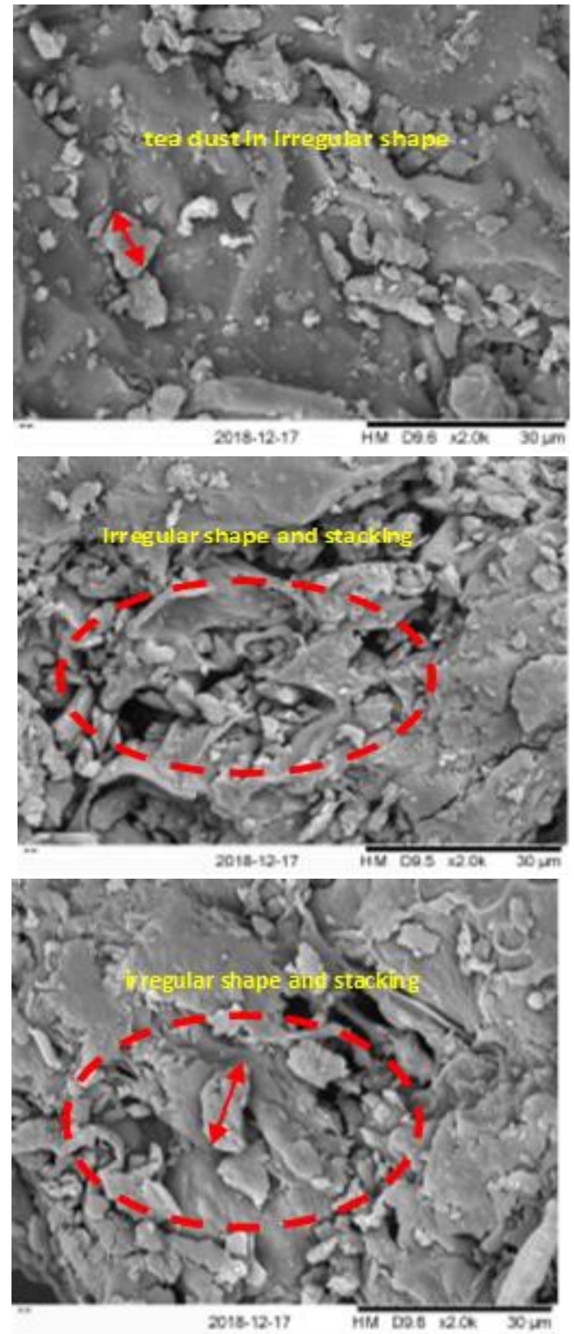


Figure 3 Scanning electron microscope image (SEM-EDX) of tea powder

3.2 Effect of Concentration

Besides particle size, explosion severity is also influenced by dust concentration, specifically the MEC. Conventionally, P_{max} would increase with increasing MEC up to a certain concentration where the fuel-air mixture is considered "rich" [22-23]. Figure 6 (top) indicates that P_{max} increases as the MEC increases up to 2000 g/m³ (P_{max}= 14.6 bar). As the MEC increases further to to 2500 g/m³, the P_{max} decreases to 12 bar respectively. Generally, this trend is comparable with the finding from Yuan *et al.* [23], suggesting that an MEC of 2500 g/m³ is a rich mixture. In a rich mixture, there would be a lot of heat loss and insufficient oxygen present in the dust cloud, which would suppress the explosion process lead to a lower P_{max} [24-26]. However, the trend is not displayed by the undried dust, for which the P_{max} always increases as the concentration increases. The highest P_{max} (8 bar) was recorded at 2500 g/m³, indicating that the MEC was at the stoichiometric condition. Figure 6 (bottom) also shows that the dP/dt trend for both particles were comparable, where the highest dP/dt was recorded at MEC=2000 g/m³ and the lowest at MEC= 1000 g/m³.

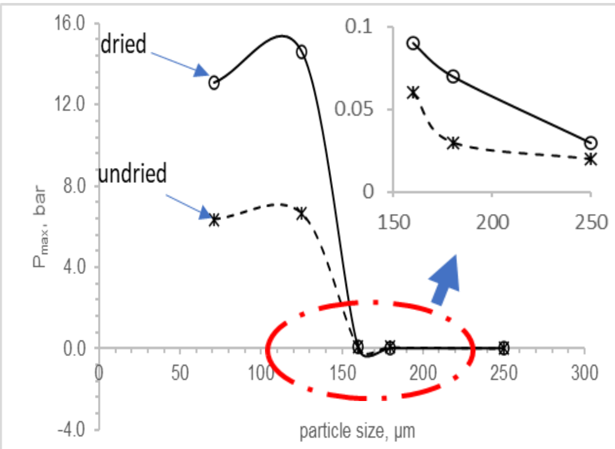


Figure 4 P_{max} trend at various tea particle sizes

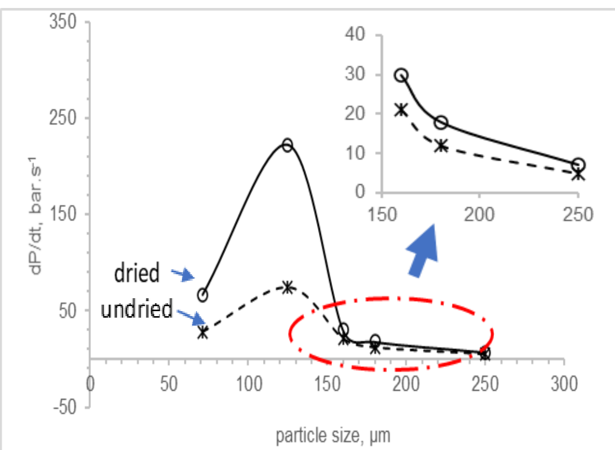
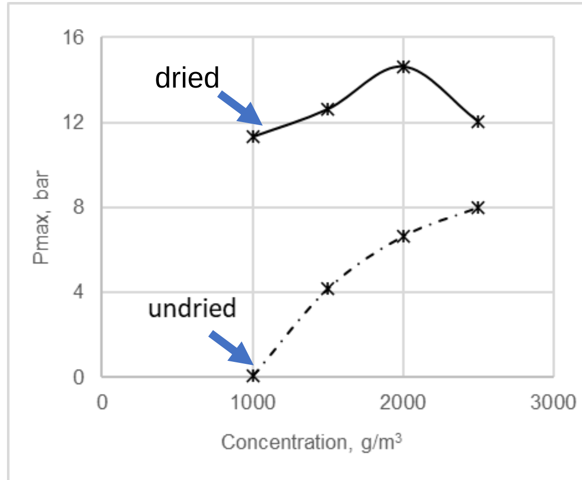


Figure 5 Rate of pressure rise, dP/dt trend at various tea particle sizes

3.3 Deflagration Index, K_{St}

K_{St}, or the deflagration index, is a critical aspect for defining the severity of a dust explosion in an enclosed space. Table 2 shows that tea powder is weakly to moderately explosible because its K_{St} value is below 200 bar.m/s for all particle sizes. At particle size 125 μm and MEC 2000 g/m³, the maximum K_{St} reading was 199.60 bar.m/s. As seen in Table 1, surface area of tea powder at 125 μm is greater, is more volatile, and has a lower moisture content than the other sizes. This describes how particles with a diameter of 125 μm had a higher K_{St}. The tea powder is classified as St 1 because its deflagration index ranges from 0 to 200 bar.m/s [27].



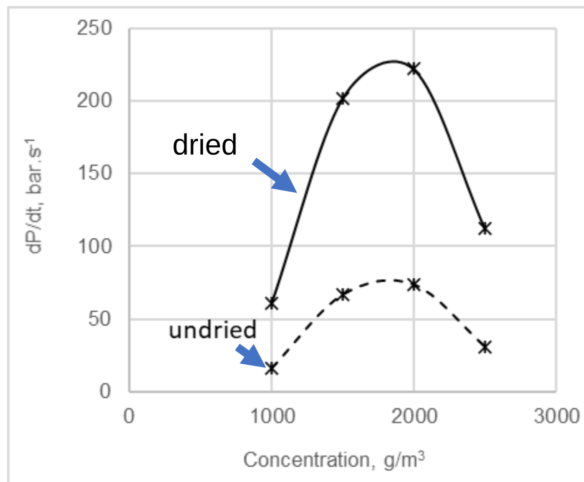


Figure 6 P_{max} (top) and dP/dt (bottom) trend at various tea concentrations

Table 2 Tea powder explosion severity at different particle sizes

Size (μm)	Median value D_{50}, (μm)	Surface area, (m²/g)	Moisture content (%)	K_{St} (bar.m/s)	Testing chamber
71	65.29	0.39	6.52	181.87	
125	91.99	0.26	8.87	199.60	20-L
160	205.03	0.10	9.08	104.72	spherical
180	243.08	0.03	10.52	67.86	chamber
250	279.53	0.02	13.54	21.72	

4.0 CONCLUSION

The influence of particle size, moisture content, and MEC on the explosion severity of tea powder was evaluated using a 20-L spherical explosion vessel. The explosion characteristic was analysed through the Pmax and dP/dt measurements from the test. It was discovered that increasing the moisture content of the tea powder decreased its explosibility. The highest P_{max} at 14.61 bar and dP/dt at 222.00 bar/s was recorded at particle size 125 µm and MEC 2000 g/m³. It was discovered that the greatest K_{St} value was 199.60 bar.m/s., which is classified as St 1. The smaller the dust, the more violent the reaction. As long as the size of the particles can sustain combustion, the rate of explosion pressure difference rises as particle size is reduced. Results obtained from this work provide tea powder explosion characteristic data, which can be used in designing the safety system for mitigating or preventing tea dust explosion incident.

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